

# Virtual Seismometers for Induced Seismicity Monitoring

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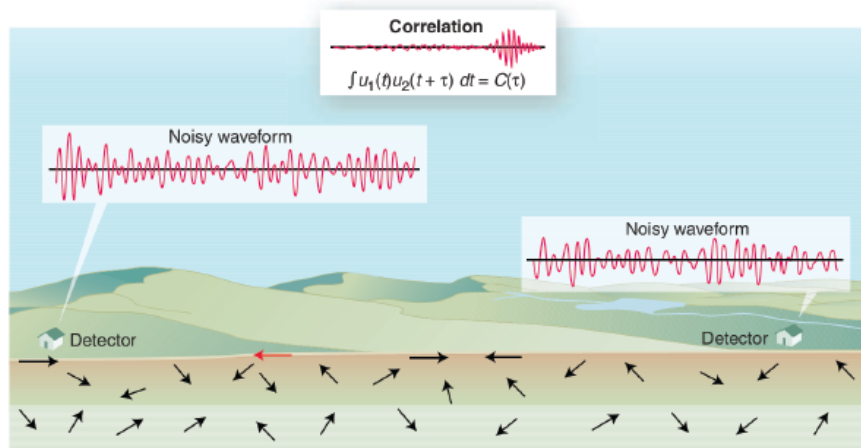
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC



# Overview

- From seismic interferometry to virtual seismometer method (VSM)
- The Newberry Enhanced Geothermal System (EGS) site
- Observed VSM at Newberry
- VSM for full focal mechanism inversion
- Conclusion

# From seismic interferometry to VSM



**Using noise in seismology.** When a diffuse wave field is generated by distant sources and/or by multiple scattering, detectors report random signals. Occasionally a ray (for example, the one shown in red) passes through both detectors. As a result, the signals are weakly correlated.

Richard L. Weaver 11 MARCH 2005 VOL 307 SCIENCE www.sciencemag.org

Lobkis & Weaver (2001) and Weaver (2005) showed that ambient seismic wavefields contain significant sensitivity to Earth structure.

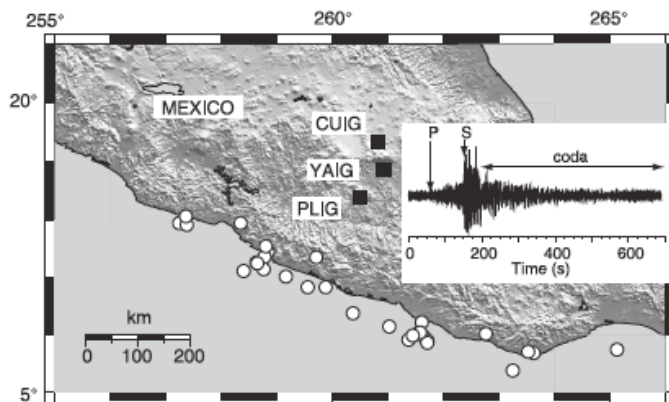
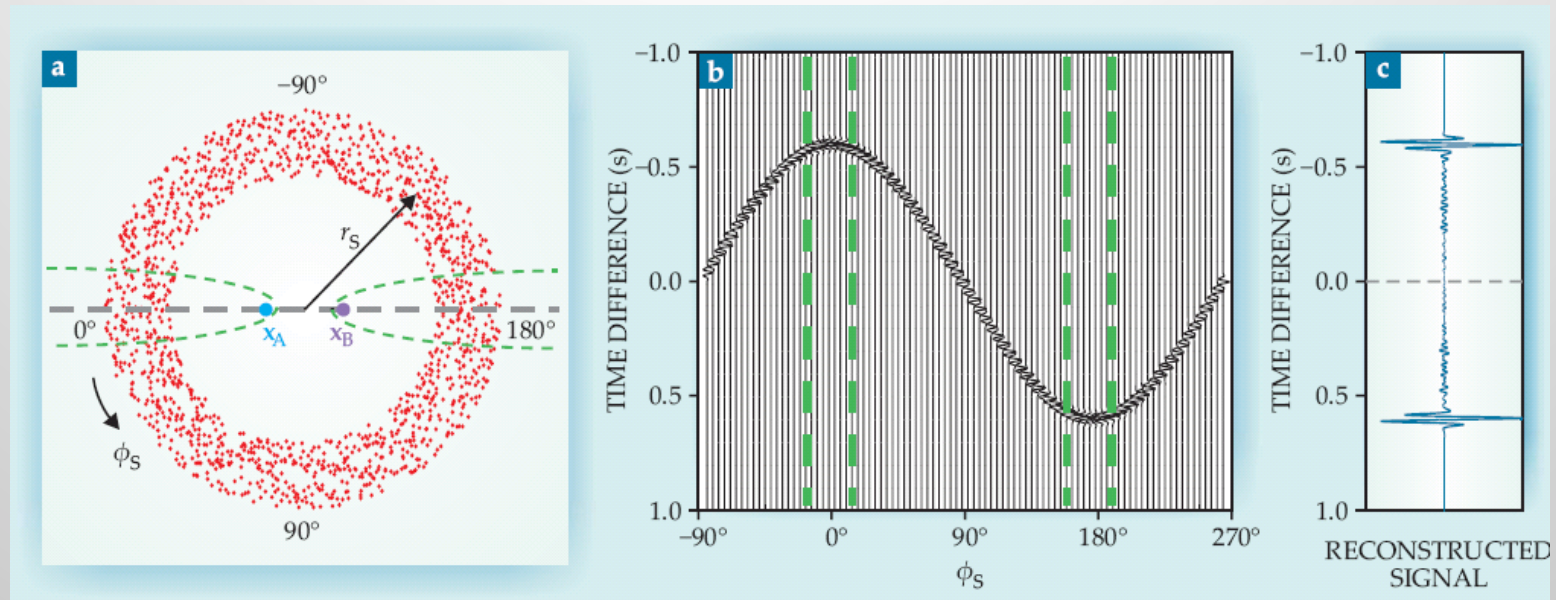


Fig. 1. Location map of the broadband stations CUIG, YAIG, and PLIG of the Mexican National Seismological Network (black squares) and epicenters of 30 earthquakes of the data set (white circles). Inset: An example of a record of one of these events at station PLIG (vertical component).

www.sciencemag.org SCIENCE VOL 299 24 JANUARY 2003  
Michel Campillo\* and Anne Paul

Campillo and Paul (2003) used the cross correlation of the diffuse coda recorded at different seismic stations to obtain the Green's function of the Earth between them.

# From seismic interferometry to VSM



- Cross-correlation of the field at two receiver positions  $x_A$  and  $x_B$  gives the response of a source at  $x_A$  observed at  $x_B$ :

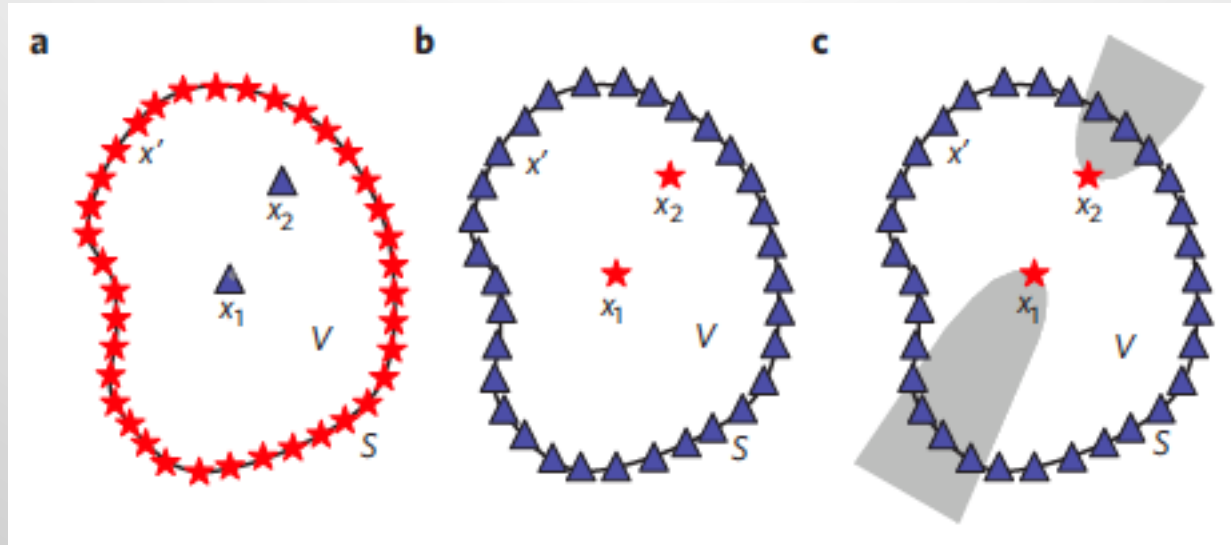
$$G(x_B, x_A, t) + G(x_B, x_A, -t) \propto \oint_{\partial D} G(x_B, x, t) * G(x_A, x, -t) d^2x$$

- Seismic Interferometry involves cross correlating and stacking diffusive waves to extract Green's functions, which can then be used for tomography.

*After Wapenaar et al., 2005*



# From seismic interferometry to VSM



## LETTERS

PUBLISHED ONLINE: 30 AUGUST 2009 | DOI: 10.1038/NGEO615

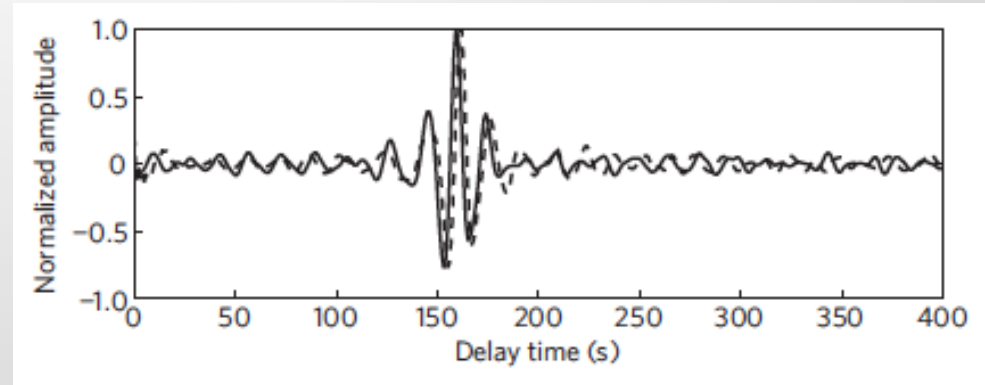
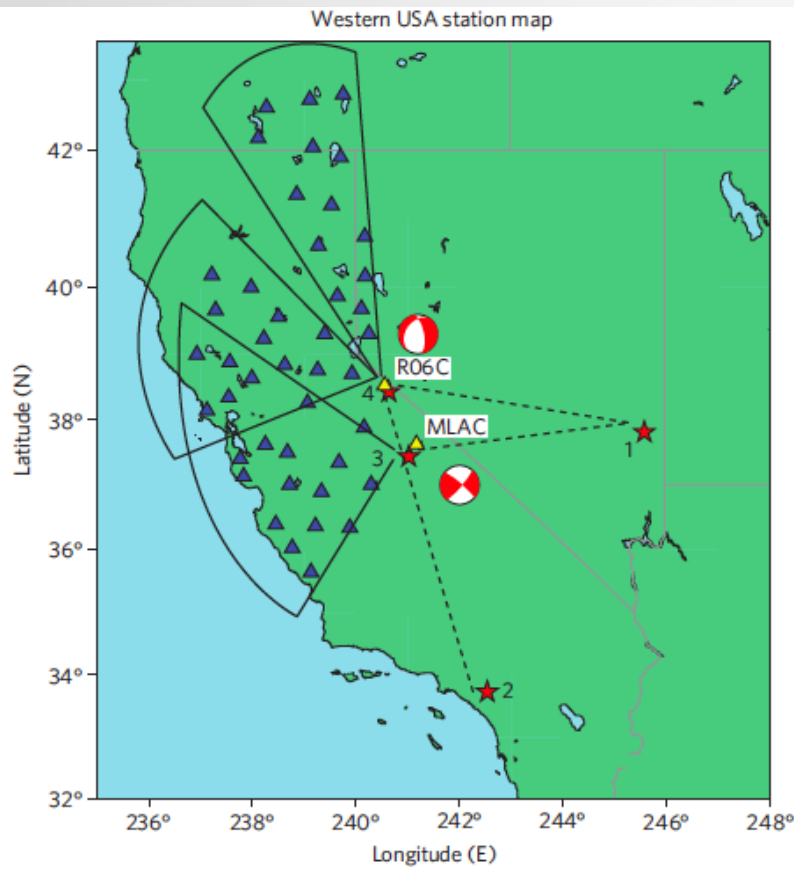
nature  
geoscience

## Virtual seismometers in the subsurface of the Earth from seismic interferometry

Andrew Curtis<sup>1,2\*</sup>, Heather Nicolson<sup>1,2,3</sup>, David Halliday<sup>1,2,4</sup>, Jeannot Trampert<sup>5</sup> and Brian Baptie<sup>2,3</sup>

# Virtual Seismometer Method

 turns earthquake into virtual seismometer



Solid line = seismogram from earthquake 1 recorded by the normal virtual seismometer 4.

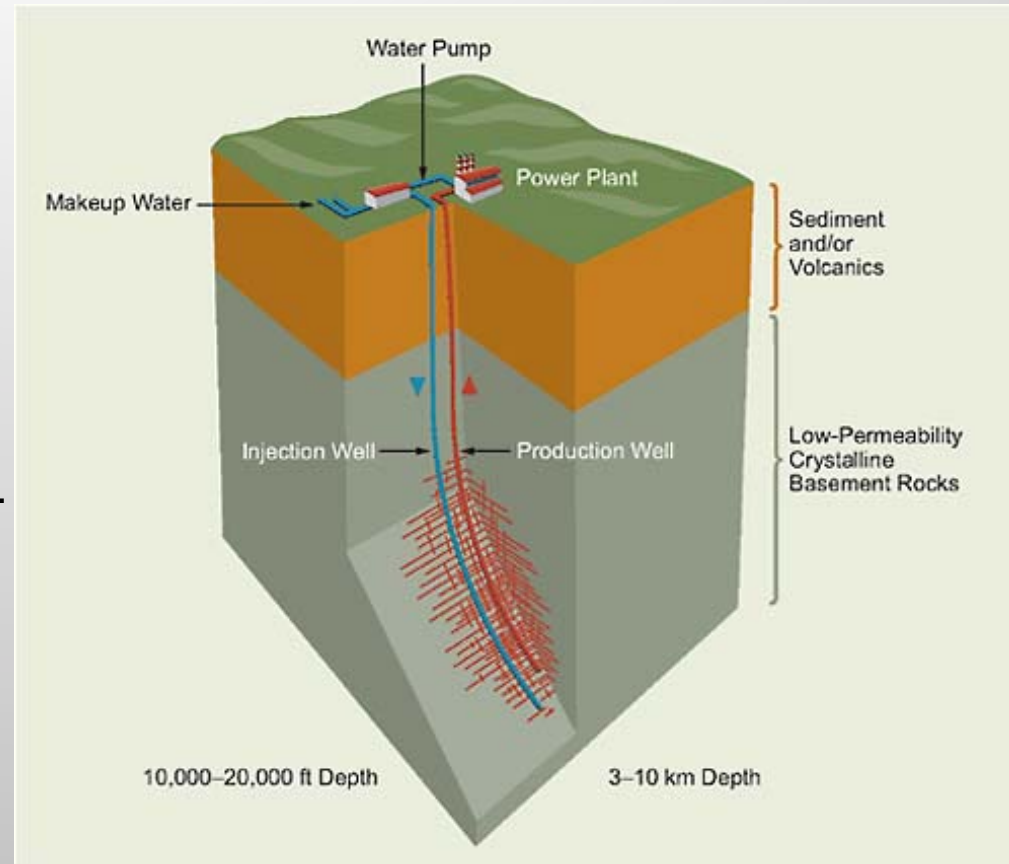
Dashed line = observed radial component seismogram from earthquake 1 recorded by the seismometer R06C.

$$M_{ip}^2 M_{mq}^1 \partial_p \partial'_q \dot{G}_{im}^h(x_2, x_1) \sim -K \int \dot{u}_n(x_2, x) \cdot \dot{u}_n^*(x_1, x) d^2 x$$

*After Curtis et al., 2009*

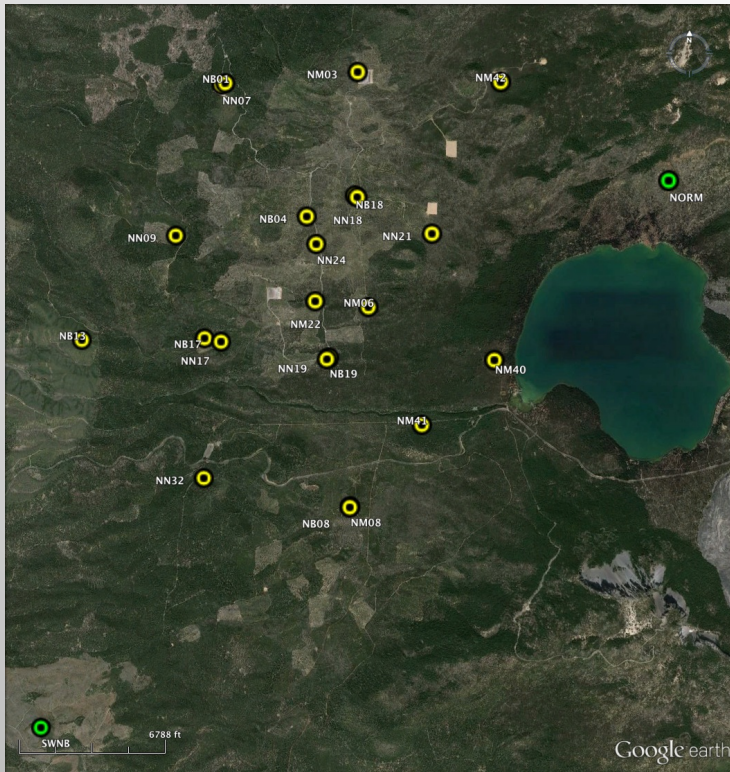
# Enhanced Geothermal System (EGS)

- Fluid circulates between injection and production wells to capture and extract heat from system.
- Requires increasing permeability by stimulating, fracturing and shearing of fractures through fluid/propanant injection.
- Importance to monitor induced seismicity in potential fault zones (e.g., Guy, Arkansas, 2010-Mw 4.7; Youngstown, Ohio, 2011-Mw 4.0; Lincoln Co., Oklahoma, 2011-Mw 5.6).

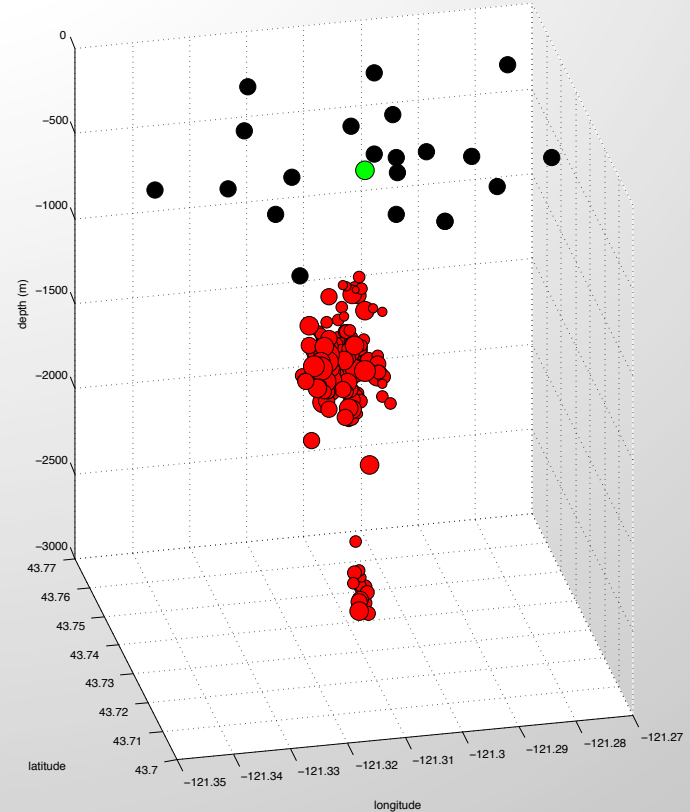


Schematic of enhanced geothermal systems using an injection and production well.  
Source: MIT, 2006.

# Newberry EGS site



Map of the Newberry experiment network.



Relocation of 180 microseismic events from October-December 2012 under Newberry using Bayesloc, a Bayesian locator developed at LLNL (*Templeton et al. 2014*).

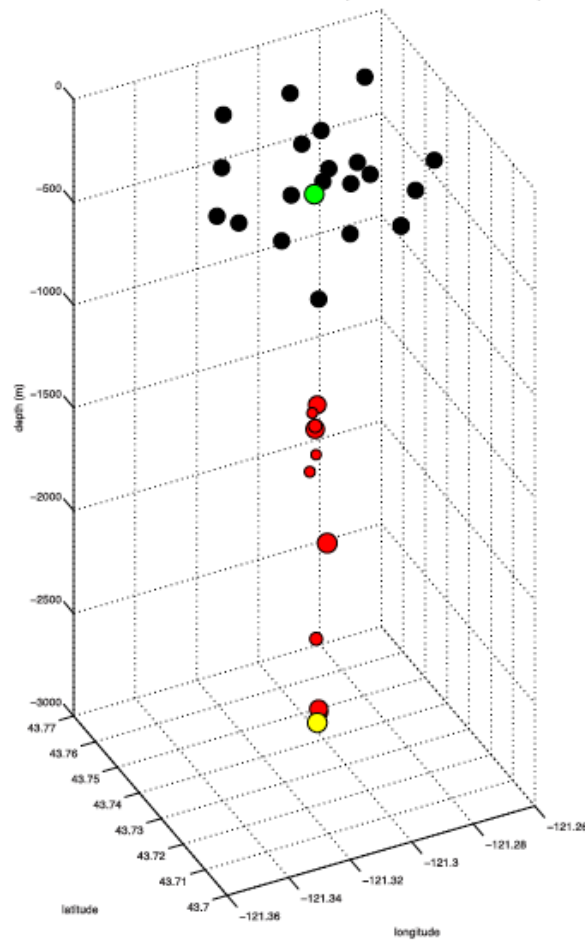
- AltaRock Energy Inc. injected water **to create a fracture network**. Water will be circulated through the fracture network where it will heat up, and be extracted via the production well and used to generate electricity.



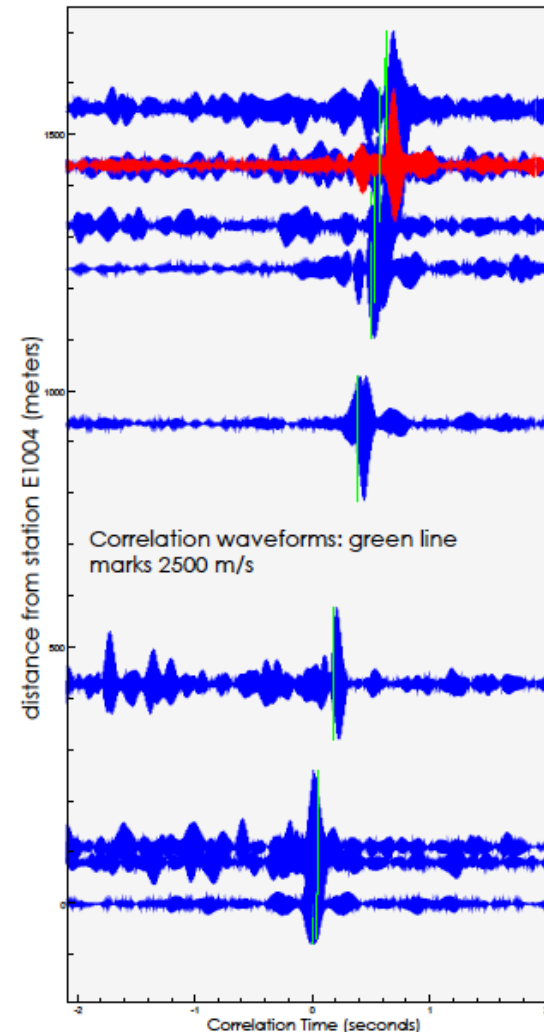
# Observed VSM at Newberry

## Example of a microquake as a virtual seismometer

Subset of the Microseismicity beneath Newberry



E1004 (yellow) as the reference virtual seismometer recording events along a line pointing towards NN24

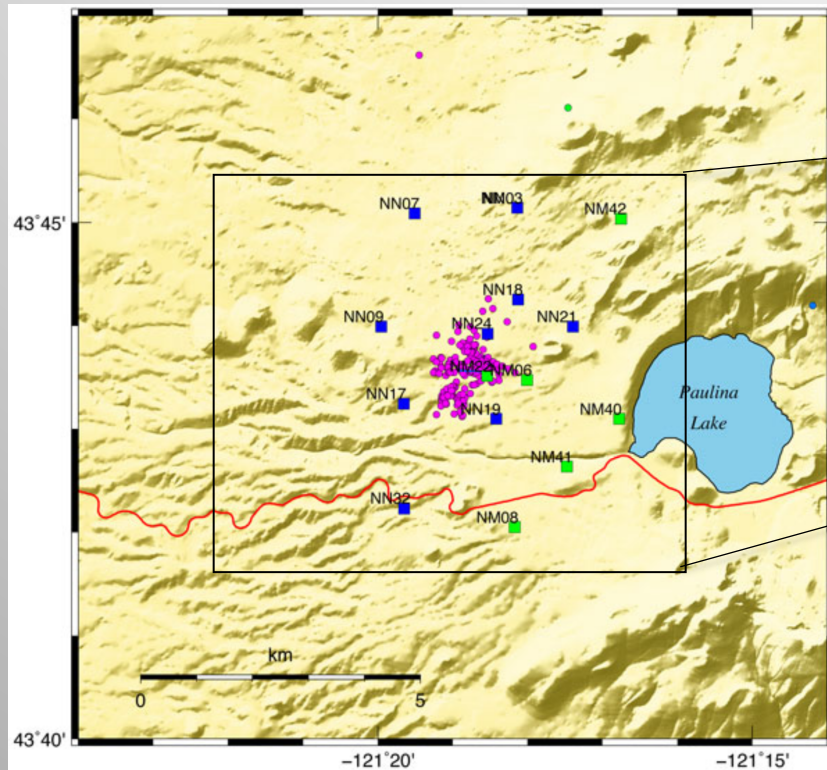


# VSM for full focal mechanism inversion at Newberry – synthetic validation

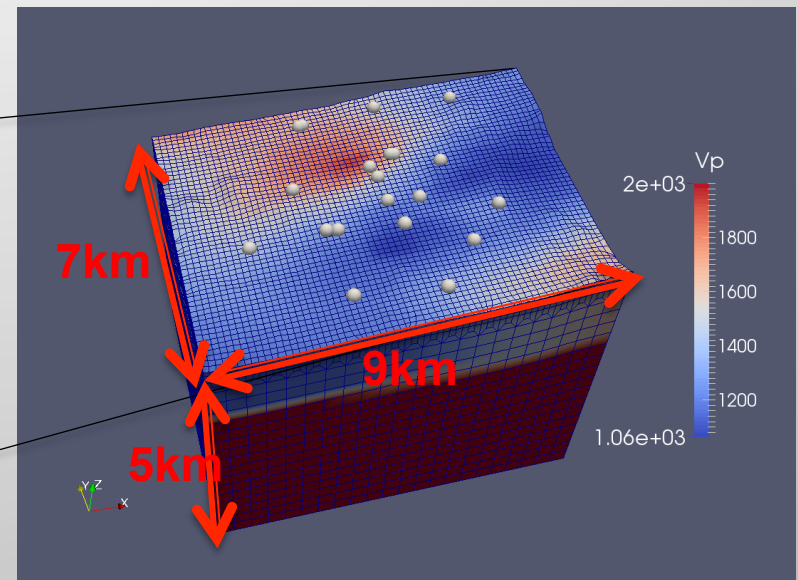
Map of microearthquakes detected in 2012

■ borehole seismometers (~200m)

■ surface seismometers

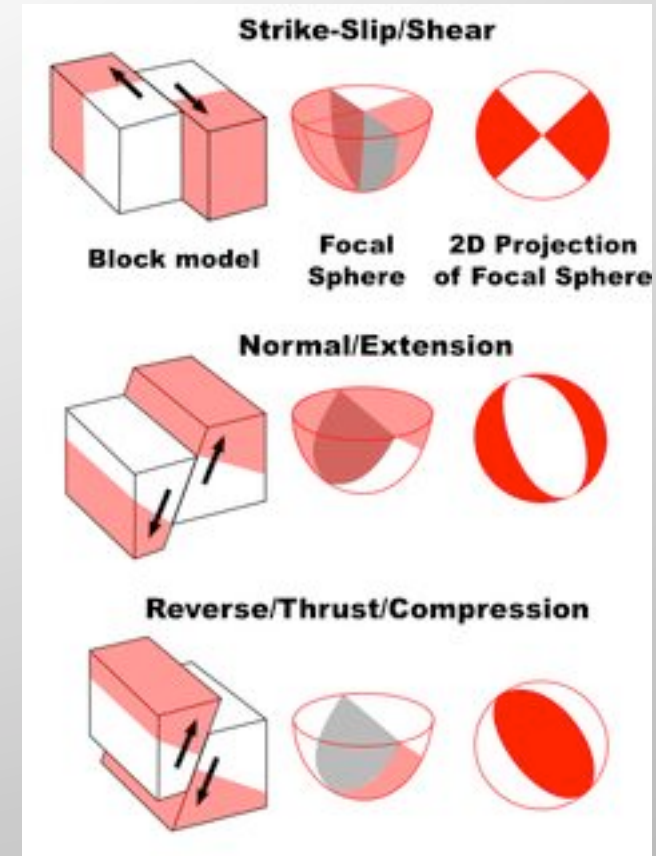
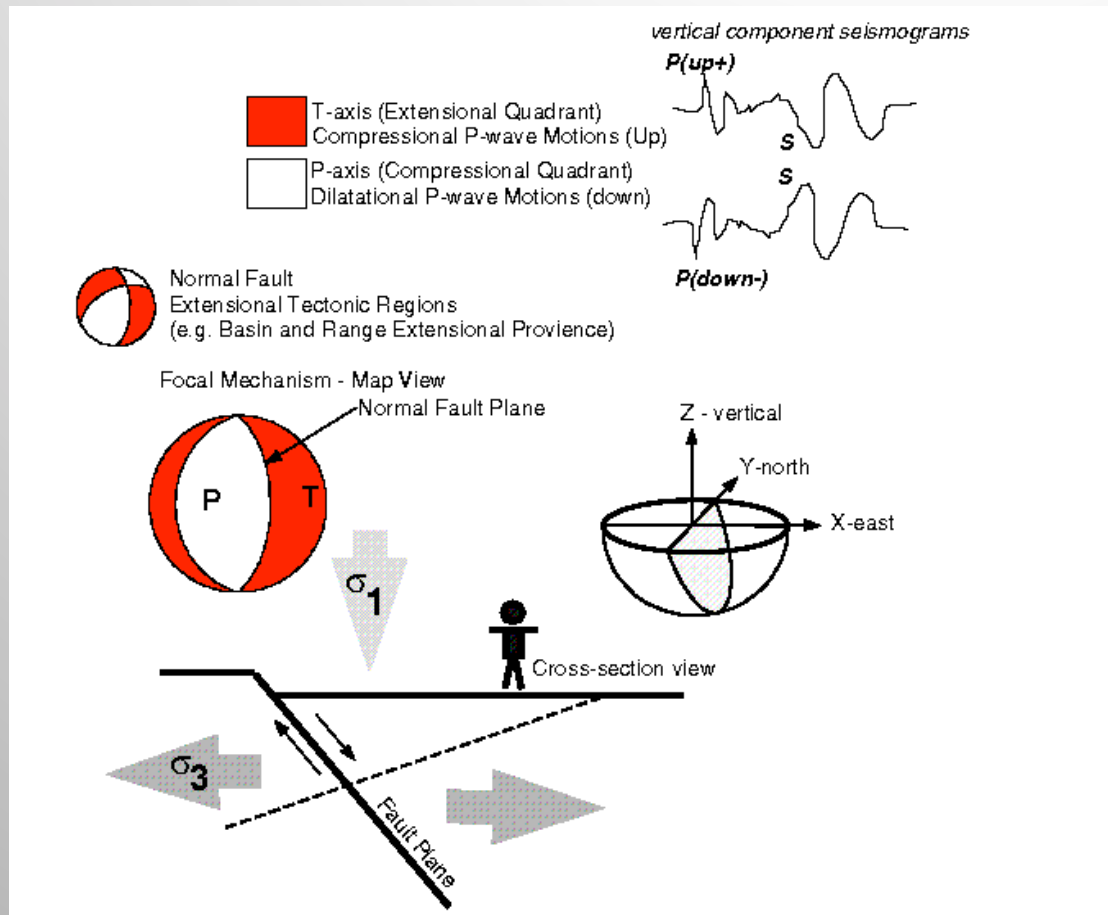


Model geometry



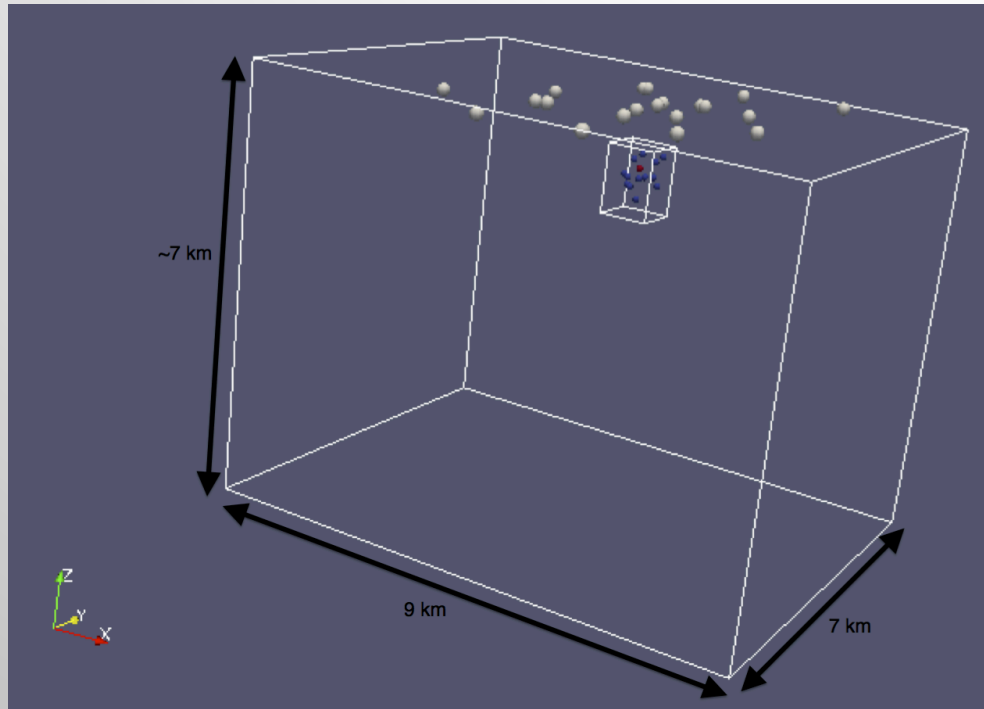
Vp 3D model and seismometers

# Focal mechanism definition



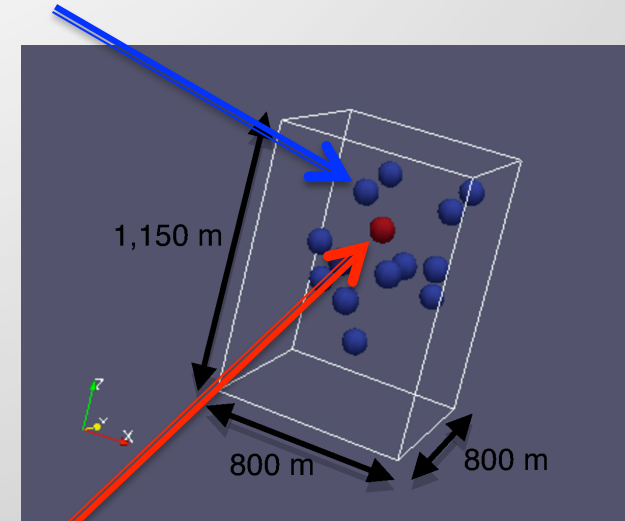
The **focal mechanism** of an earthquake describes the deformation in the source region that generates the seismic waves. In the case of a fault-related event it refers to the orientation of the fault plane that slipped and the slip vector and is also known as a fault-plane solution.

# 3D Newberry – Synthetic validation



*Initial full domain*

virtual  
seismometers  $x_1^j$



*Subdomain*

microseismic  
event  $x_2$

## Protocol:

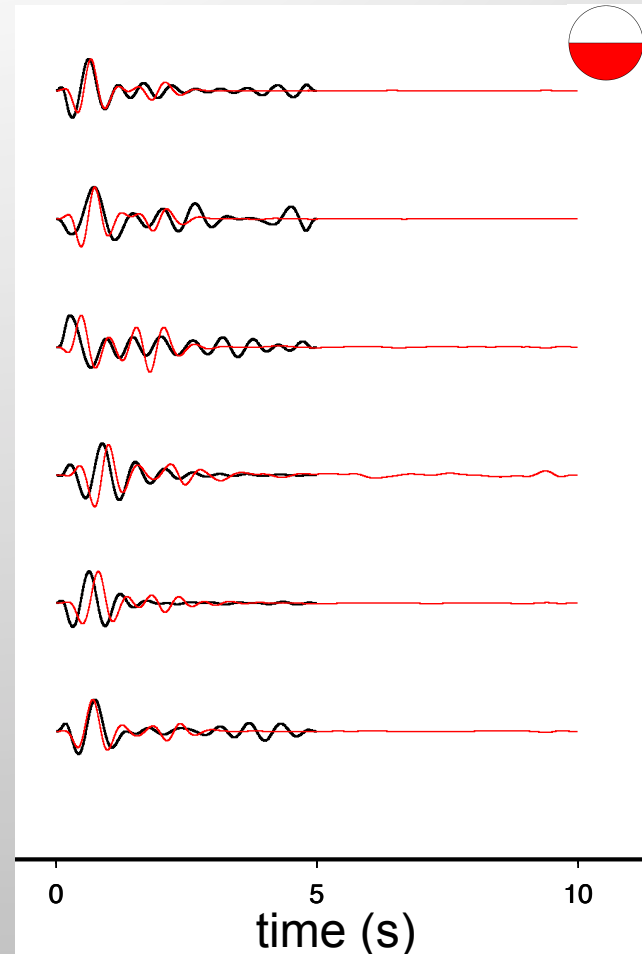
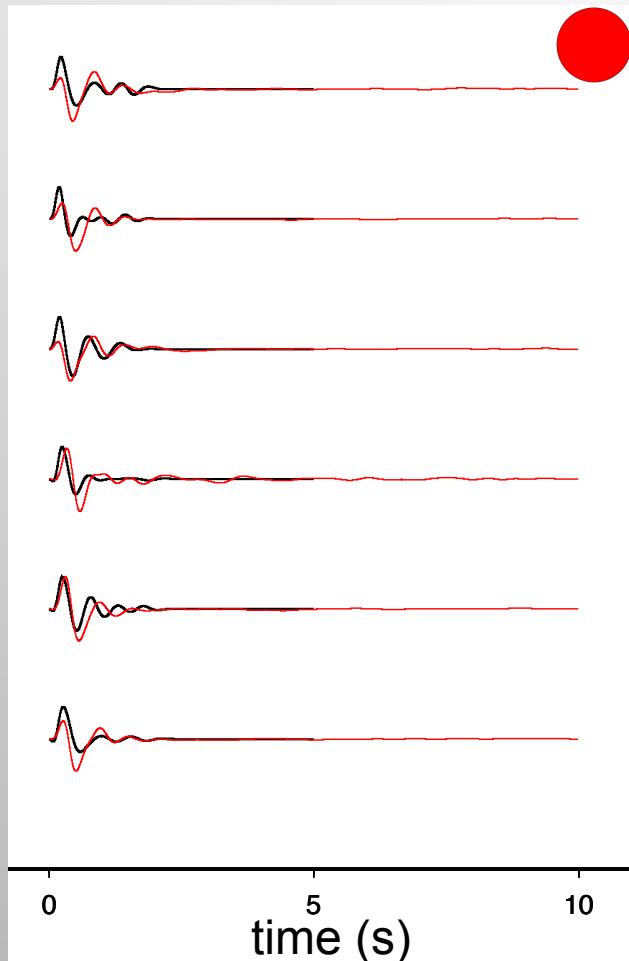
- 1) Record microevents  $x_1^j$  and  $x_2$  at the classical seismometers at the surface (initial domain)
- 2) Cross-correlate waveforms of every source  $x_1^j$  with  $x_2$
- 3) Calculate strain rates of each event  $x_1^j$  as recorded by  $x_2$  (subdomain)
- 4) Invert for the focal mechanism at  $x_2$  based on least square method



# 3D Newberry – Synthetic validation



Comparison to the known solution, example of two focal mechanisms



$$M_{ip}^2 M_{mq}^1 \partial_p \partial'_q \dot{G}_{im}^h(x_2, x_1) \sim -K \int \dot{u}_n(x_2, x) \cdot \dot{u}_n^*(x_1, x) d^2 x$$

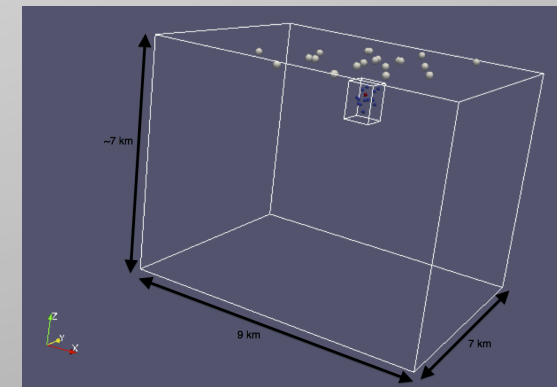
# 3D Newberry – Synthetic validation

1) cross correlation of observed dataset at the surface

2) synthetic strain rates calculated within the micro events cloud domain

$$M_{ip}^2 M_{mq}^1 \partial_p \partial'_q \dot{G}_{im}^h(x_2, x_1) \sim -K \int \dot{u}_n(x_2, x) \cdot \dot{u}_n^*(x_1, x) d^2 x$$

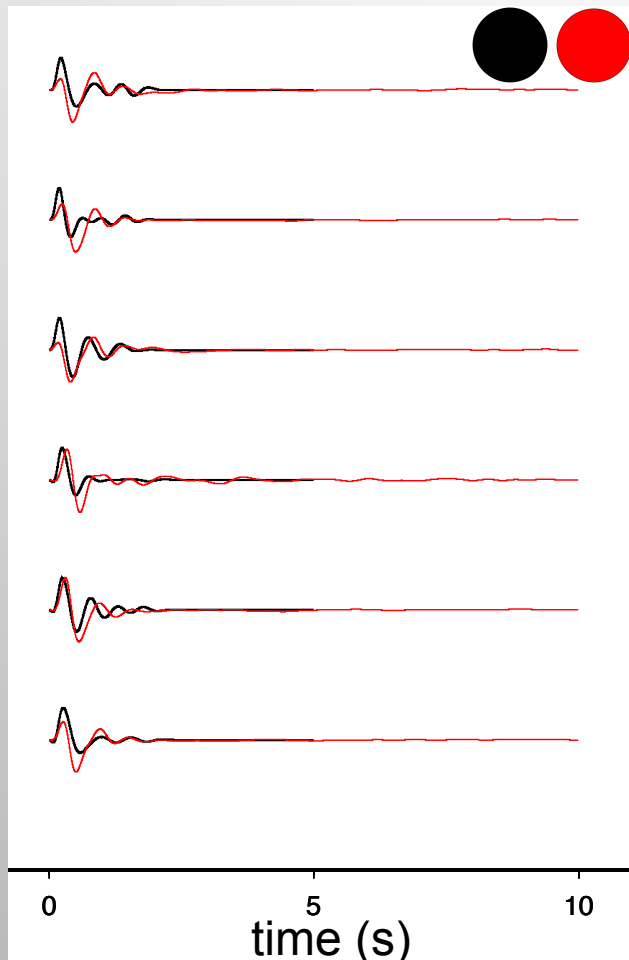
**3) inverted focal mechanism**



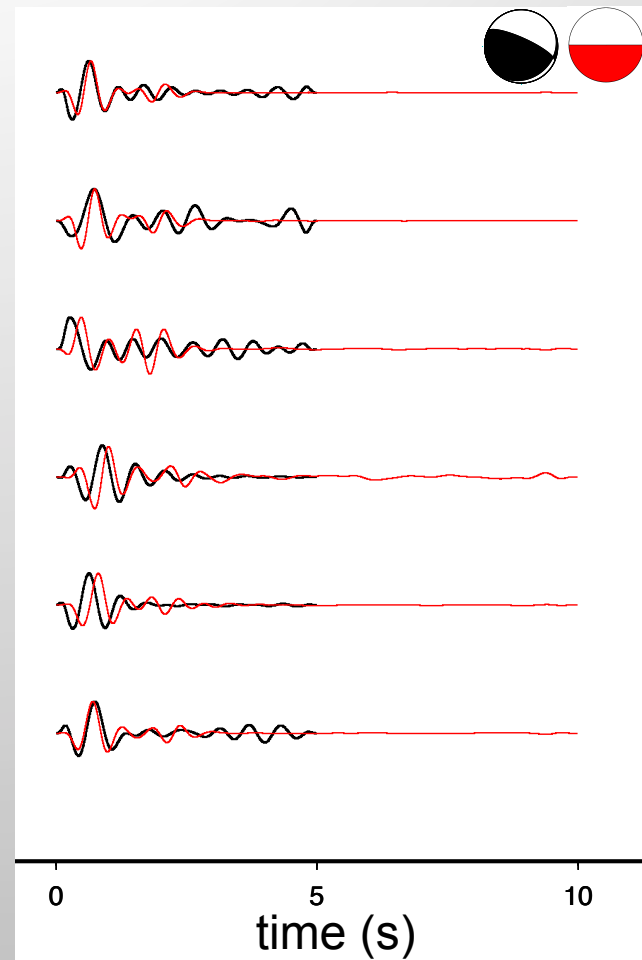
# 3D Newberry – Synthetic validation



Result of the inversion (black focal mechanism)



ISO = 82%  
DC = 14%  
CLVD = 4%



ISO = 43%  
DC = 51%  
CLVD = 6%

# Conclusion

- VSM allows to virtually place seismometers inside a micro events cloud.
- Virtual seismometers record strain measurements contrary to classical seismometers measuring displacements.
- With VSM we only need to numerically model a small subset of domain around the micro events cloud – enabling better resolution.
- VSM was used to recover full focal mechanism and allows us to focus on properties directly between induced micro events.
- VSM can be used to track relative difference between two focal mechanisms which can be indicative of different fracture openings.



